Scarcity climate rents under a carbon price with oligopoly competition

By Francisco J. André [a] and Luis M. de Castro [b]

a Department of Economic Analysis. Universidad Complutense de Madrid, Campus de Somosaguas, 28223 Madrid, Spain; e-mail: andre@ccee.ucm.es
b Department of Economic Analysis. Universidad Complutense de Madrid

ABSTRACT

Prior research has shown that environmental policy can create scarcity rents. We analyse this phenomenon in the framework of a duopoly that faces a carbon price, considering both Cournot and Stackelberg competition. We identify the different sources of scarcity rents, which we classify in "output" and "grandfathering" scarcity rents. The former depend on the elasticity of the rivals' output to the carbon price while the latter is exogenous. We also determine under which conditions these rents can be large enough to increase firms' profits and, as a policy implication, to what extent the existence of scarcity rents can make the firms agree on a tougher policy. This event is more likely to happen under Cournot than under Stackelberg competition, and the chances increase if the firms are allowed to pollute a large amount without paying a price.

JEL code: D43, L13, Q58

1. Introduction

This paper examines the creation of scarcity rents for oligopolistic firms due to the existence of a carbon price. We model the mechanisms that give rise to scarcity rents and identify the circumstances under which such rents can be large enough to offset the costs to comply with a tougher environmental policy.

Climate change is probably the most salient transboundary environmental problem. It was a reason behind the creation of the United Nations Framework Convention on Climate Change in 1992 and its relevance within the policy agenda has been steadily increasing.

Among economists, the most popular approach to deal with climate change is to set a carbon price by either introducing carbon taxes or by creating carbon markets (see, e.g. Tietenberg (2010) or Elkins and Baker (2001) for an overview of both policy approaches and some examples of their practical application). As noted by Convery (2009), the European Union (EU) initially planned to create a carbon tax, but the failure of this project gave rise to the European Union Emissions Trading System (EU ETS), which is now a major pillar of the EU climate policy.

It is well established in the literature that some environmental policies can create scarcity rents for firms, which in the case of climate policies are sometimes known as *climate rents*. This effect can arise with carbon taxes, but is perhaps more clearly visible in emission trading, as some firms can obtain additional revenue by selling permits. Empirical evidence suggests that this phenomenon has been rather important in the first phase of the EU ETS. A less obvious effect comes through the output market. A higher carbon price represents a higher cost for firms, which will react by producing less output and increasing prices. This induced effect can alleviate or even more than fully compensate the compliance costs, resulting in higher profits.

We focus on two components of climate policy and their impact on climate rents: first, a marginal effect, which is the carbon price itself. In the case of a permit trading system, this refers to the permit price prevailing in the market. In the case of an emission tax, it is the tax rate. The second element is a fixed-term effect, which measures the amount of carbon that firms can emit without paying a price. In the case of a cap-and-trade system, this takes the form of a certain number of free permits distributed among the firms by means of grandfathering. In the case of a tax, it refers to a tax exemption. For simplicity we will always refer to this effect as “grandfathering”.

We set up a duopoly model in which each firm has to pay a carbon price for (a part of) its emissions. In the output market we allow for Cournot or Stackelberg competition. We show that a higher carbon price increases the firms’ cost of complying with the policy, but it also has two positive effects on profits. First, it restricts output and increases the output price as well as firms' revenues, which we call "output scarcity rent". The share of this type of rents that accrues to a specific firm depends on the elasticity of its rival's output with respect to the carbon price, which implies that a monopoly can never obtain output scarcity rents as we define them. The second positive effect is labelled “grandfathering scarcity rents” and is due to the fact that a higher carbon price increases the market value of the amount of emissions that are exempt.

We explore a particular case with a separable cost function and linear demand to gain some further insights. As the first core finding we conclude that both firms face a profit function that is convex in the carbon price, which implies that, when the price is sufficiently low, both firms will benefit from a price reduction, whereas with sufficiently high prices, they will benefit from further increases. Apart from these two regions, in the Stackelberg model there is an intermediate interval in which both firms' interests are decoupled because the leader's profit is decreasing while the follower's is increasing.

As a policy application of our results, we ask how likely it is that the firms are willing to accept a tougher climate policy. This is a relevant question from a political economy point of view as any policy is more prone to be successful if the firms that will be affected are willing to accept it. We conclude that firms are more likely to agree on a tougher policy when they compete on an equal footing, as in the Cournot setting, whereas the existence of leaders and followers tends to create a wedge between the interests of both firms.

Grandfathering makes the firms more likely to benefit from an increase in the carbon price. If grandfathering is large enough, the firms may be willing to accept a tougher policy, whatever the starting point. In the Stackelberg case there is a qualitatively stronger implication that leads us to conclude that, in the absence of grandfathering, the firms would never agree on a tougher policy as the agreement region shrinks to such an extent that it may disappear. Therefore, in a Stackelberg setting, the existence of grandfathering seems crucial for policy acceptability.

As a sensitivity analysis, we allow for parameter asymmetries. In the Stackelberg case, we conclude that the willingness to accept a tougher policy is sensitive to the amount of the leader's (but not the follower's) emissions that are exempt. Moreover, those parameter changes that tend to undermine the leader's advantage in the output market (an increase in the leader's output cost or a decrease in the follower's) make the firms more symmetric in a certain sense and increase the likelihood of agreement. The opposite occurs with abatement costs: the likelihood of agreement tends to decrease with the leader's abatement cost and increase with the follower's.

The closest papers to ours are those dealing, on the one hand, with scarcity rents and the impact of carbon prices on firms' profits and, on the other hand, with carbon markets and market power. For a broad discussion on scarcity rents, see e.g. Fullerton and Metcalf (2001). In a perfect competition framework, Mohr and Saha (2008) claim that, via the generation of scarcity rents, a stricter environmental regulation might increase firms' profits and pass the cost onto consumers. André *et al.* (2009) make a similar point in a strategic setting with quality competition. MacKenzie and Ohndorf (2012) claim that both revenue-raising instruments, e.g. emission taxes or auctioned permits, and non-revenue-raising instruments, such as freely allocated tradable permits, can create scarcity rents that may be susceptible to costly appropriation activities. Kalkuhl and Brecha (2013) find that reducing fossil resource use could increase scarcity rents and benefit fossil resource owners under a permit grandfathering rule. Newell *et al.* (2013) report that the power generators extracted rents by receiving carbon allowances for free and then passing on the opportunity costs of these allowances to their customers. Moreover, some firms have taken the opportunity to sell a part of their permit allocation and get extra revenue. For an analysis of this phenomenon, see e.g. Sijm *et al.* (2006) or Ellerman *et al.* (2010).

Several authors have addressed the existence of market power in the carbon markets and/or in the associated product markets. Hahn (1984) was the first to note that, with a dominant firm in the emission market, the resulting equilibrium is not cost-effective in general, and the efficiency loss depends on the initial allocation. Other studies have explored the consequences of market power in the emissions market under different settings. For a survey see Montero (2009).

Other authors have shown that perfect competition in the carbon market might not be sufficient to render a cost-effective outcome if the product market is not perfectly competitive. In a Cournot duopoly, Sartzetakis (1997) shows that (competitive) emission trading modifies the allocation of emissions among firms and hence their production choices. Sartzetakis (2004) shows that welfare can decrease when emission trading is allowed between asymmetric firms endowed with different technologies. Meunier (2011) concludes that even if the firms are price takers in the emission market, the integration of such markets can decrease welfare because of imperfect competition in product markets. There are also some papers that consider market power in both permit and output markets. See, e.g. Misiolek and Elder (1989), Eshel (2005) Hinterman (2011, 2015) or De Feo et al. (2013).

This paper considers market power in the product market, but not in the carbon market. The reason is threefold. First, as noted by Montero (2009), while market power is very common in output markets, the existence of market power in carbon markets is more likely to appear when the relevant players are countries rather than firms. In the latter case, there are normally a very large number of participants, which makes it difficult for market power to arise. It can be argued that this is the case in the EU ETS, with more than 11,000 facilities involved. Moreover, the latest steps taken by the European Commission seem to be aimed at increasing the degree of competition even more (by increasing the number of involved sectors, centralising the allocation of permits and moving from grandfathering to auctioning). On the other hand, among the economic sectors that are subject to the EU ETS, it is realistic to assume that at least in some of them there is some market power (see, e.g. Smale et al. 2006 or Hinterman 2011).

Second, the EU ETS price shock in 2005 generated a great deal of interest in market power. Initially, the price of allowances was far in excess of expectations, but it suddenly fell in April 2006, reaching zero in mid-2007. Empirical studies have not been able to sufficiently explain these excessively high price levels when the number of permits exceeded emissions in every year of the first phase (see, e.g. Ellerman et al. 2010). It is therefore natural to ask whether the reason for these price variations might be linked to the output market rather than the permit market insofar as permits could somehow be used to obtain windfall profits in the output market.

And third, we are interested in modelling how an increase in the carbon price impacts on the firms' profits rather than explaining the origin of this increase. Our central conclusions do not crucially depend on the carbon price being determined by a tax or a permit trading system, as far as such a price is taken as exogenous. Therefore, we do not model the carbon market itself, but simply take the carbon price as a given indicator of the policy stringency.

A somewhat related paper is Ehrhart *et al.* (2008), which show that under some conditions firms can benefit from a higher price of permits. In contrast to their analysis, we consider grandfathering, which allows us to make an explicit characterisation of the different sources of scarcity rents. Moreover, we compare Cournot vs. Stackelberg settings, while Ehrhart *et al.* restrict themselves to situations in which the firms play exactly the same role in the market. We are not aware of any paper in the related literature that compares Cournot and Stackelberg settings. Another difference is our detailed study of a particular case, which renders some insights that cannot be derived in a general model.

Section 2 presents the basic model. A particular abatement cost function is considered in Section 3. Section 4 investigates the possibility that firms can agree on a tougher policy. Section 5 concludes. All the proofs are gathered in an appendix.

2. The general model

Consider a duopolistic polluting industry that faces an exogenous carbon price, p. To fix ideas, we consider that such a price is determined within a permit trading system, although most of our discussion is also valid for a tax.[1]

The cost function of firm $i \in (1, 2)$, $C_i(x_i, e_i)$, depends on output (x_i) and emissions (e_i) and is continuous and twice differentiable in both arguments with the following properties:

$$\frac{\partial C_i}{\partial x_i} > 0, \quad \frac{\partial C_i}{\partial e_i} < 0, \quad \frac{\partial^2 C_i}{\partial e_i^2} > 0, \quad \frac{\partial^2 C_i}{\partial x_i \partial e_i} < 0. \tag{1}$$

[1] Provided that the carbon price is exogenous, a carbon market and a tax are basically equivalent for any firm that pollutes above its initial allocation. The main difference is that, in a market, a firm that pollutes below its permit allocation can sell permits and raise some revenue. This possibility can be replicated if the tax is combined with a subsidy for those firms that pollute below the exempt amount. See Goulder and Schein (2013) for a discussion on the relationship between permit trading and carbon taxes.

This function integrates production and abatement costs and reflects the fact that producing clean is more costly than producing dirty. There is a carbon price p that the firms take as exogenous,[2] so that each firm i has to pay p monetary units for each unit of emissions except for the first S_i, which is an amount of free permits received by means of grandfathering.[3] Total cost is then given by

$$TC_i\left(x_i, e_i\right) := C_i\left(x_i, e_i\right) + p\left(e_i - S_i\right). \tag{2}$$

We assume the following timing. In the first stage, the firms compete in the output market by choosing their output levels, x_1 and x_2, facing the inverse demand function $P\left(X\right)$, where $X := x_1 + x_2$, $\frac{dp}{dX} < 0$. In the Cournot version the output decisions are simultaneous. In the Stackelberg case this first stage has two sub-stages: first the leader decides x_1 and then the follower sets x_2. In the second stage, both firms simultaneously choose their emission levels, e_i $(i = 1, 2)$ to minimize their total cost, $TC_i\left(x_i, e_i\right)$, while taking their output levels and the carbon price as given.

To find a subgame-perfect Nash equilibrium, we solve the model backwards. In the final stage, if the solution is interior, the first-order conditions (FOC) are

$$\frac{\partial C_i}{\partial e_i} + p = 0, \quad i = 1, 2, \tag{3}$$

which implicitly defines each firm's optimal amount of emissions, $e_i^*\left(x_i, p\right)$.[4] Using this expression in (2) we obtain the minimized total cost function in terms of output and the carbon price:

$$TC_i^*\left(x_i, p\right) := TC\left(x_i, e_i^*\left(x_i, p\right)\right) = C\left(x_i, e_i^*\left(x_i, p\right)\right) + p\left[e_i^*\left(x_i, p\right) - S_i\right] \tag{4}$$

---

[2] To interpret why the firms take the carbon price as exogenous, consider that this price is determined in a wider market in which other firms from different industries take part (as is the case, e.g. in the EU ETS).

[3] Under a carbon tax S_i can be seen as a tax exemption.

[4] The second order condition is always fulfilled due to the convexity of C_i in emissions. Throughout the paper, we restrict the analysis to interior solutions. Asterisks denote equilibrium values.

and using the envelope theorem we get

$$\frac{\partial TC_i^*}{\partial p} = e_i^* - S_i \,, \tag{5}$$

which simply states that the marginal impact of the carbon price on total cost equals the amount of emissions that are not exempt.

Now we move on to the first stage of the game, the output market. Each firm maximizes its profit, defined as

$$\Pi_i = P \cdot x_i - TC_i^*\left(x_i, p\right).$$

We address Cournot and Stackelberg competition separately in the following subsections.

2.1 Cournot

Consider first that both firms decide their output levels simultaneously taking the rival's output as given. Firm *i*'s FOC is

$$P\left(x_i + x_{-i}\right) + \frac{\partial P}{\partial X} x_i - \frac{\partial TC_i}{\partial x_i} = 0 \,, \tag{6}$$

where "$-i$" refers to the other firm. This equation implicitly defines the reaction function of firm i:

$$x_i = x_i^R\left(x_{-i}, p\right). \tag{7}$$

Using the implicit function theorem, we conclude that one firm´s output is decreasing in its rival´s output and the carbon price:

$$\frac{\partial x_i^R}{\partial x_{-i}} = \frac{-\,{}^{dP}\!/_{dX}}{2\,{}^{dP}\!/_{dX} - {}^{\partial^2 TC_i}\!/_{\partial x_i^2}} < 0 \,, \quad \frac{\partial x_i^R}{\partial p} = \frac{{}^{\partial^2 TC_i}\!/_{\partial x \partial p}}{2\,{}^{dP}\!/_{dX} - {}^{\partial^2 TC_i}\!/_{\partial x_i^2}} < 0 \,, \tag{8}$$

where the second order condition requires that the denominator of both expressions is negative.[5]

The system of equations formed by both reaction functions determine the final equilibrium as a function of the carbon price, p , and using the equilibrium value of output we can also write both agents′ profits as a function of p :

$$\Pi_i^*\left(p\right) := P\left(x_i^* + x_{-i}^*\right)x_i^* - TC\left(x_i^*, e_i^*\right). \tag{9}$$

Our main research question is to what extent, and by which channels, a higher carbon price can benefit firms.[6] Differentiating (9) with respect to p and using equations (4) and (6) we obtain

$$\frac{d\Pi_i^*}{\partial p} = \underbrace{S_i}_{SR_i^G} + \underbrace{\frac{dP}{\partial X}\frac{\partial x_{-i}^*}{\partial p}x_i^*}_{SR_i^x} - e_i^*, \tag{10}$$

from which we conclude that the marginal effect of the carbon price on profits can be split in three components. The two first effects (SR^x and SR^G) are positive and account for the scarcity rents for firm i . The third component is negative and determines what part of the scarcity rents each firm can capture.

The first component, which we label "grandfathering scarcity rent", is exogenous and simply equals the amount of emissions that are exempt from paying the carbon price. The second term is endogenous and represents the additional revenue that each firm will receive thanks to the reduction in output supply and the resulting increase in the output price. We call it "output scarcity rent".

Note that a higher value of p causes the output of both firms, and hence total output, to decrease, which pushes the price up, but each firm can benefit only from the part of this

[5] A sufficient (not necessary) condition for the second order conditions to hold is that TC_i^* is convex in output.

[6] It is important to note that our results are marginal, not discrete, in the sense that we only consider increases in the carbon price. So, throughout the whole paper, we are considering that a policy that is already in place gets tougher, not that a new policy is introduced.

effect that is due to its rival's output reduction, $\partial x_{-i}^{*} / \partial p$. The reason is that reducing your own output has both a positive effect (by increasing the price and decreasing the cost) and a negative effect (decreasing the number of sold units) and in equilibrium both effects cancel out each other because of the first order maximum profit conditions. The reduction in the rival's production, on the contrary, causes output price to rise without having any negative side-effect for firm i. A consequence of this result is that a monopoly would never obtain positive output scarcity rents because of an increase in the carbon price. The only channel by which a monopoly could benefit from a higher p is the grandfathering scarcity rent, and only if $S_i > e_i^*$, i.e., if it is a net seller of permits.

From (10) we immediately obtain $SR_1^x \geq SR_2^x \Leftrightarrow \varepsilon_{x_2^*, p} \geq \varepsilon_{x_1^*, p}$, where $\varepsilon_{A,B}$ denotes the elasticity of A with respect to B, i.e., a firm enjoys more output scarcity rents than its rival if its rival's output is more sensitive to the carbon price than its own output.

The last term in (10) is the equilibrium amount of emissions or, equivalently, the required permits, which determine the part of the scarcity rents that firm i is not able to capture. Who gets that part of the rents depends on how the firm obtains the permits. If they are auctioned, it is the auctioneer (typically the environmental authority) who gets the rents (and this is also the case under a tax). If the permits are bought in the secondary market, the rents are transferred to the seller.

Altogether, the first and third summands in (10) represent the net purchase (if $S_i < e_i^*$) or sell ($S_i > e_i^*$) of permits by firm i. If $S_i > e_i^*$, firm i initially receives more permits than needed and it would get an extra profit by selling some permits, which can be naturally interpreted as a scarcity rent since the firm is getting some revenue by selling a scarce asset. If $S_i < e_i^*$ the firm is a net buyer of permits, but we continue to interpret S_i as a scarcity rent in the sense that it allows the firm to finance for free part of the external cost caused by its own emissions. In the limiting case, $S_i = e_i^*$, all the equilibrium emissions are exactly covered with free permits. Then, an increase in the carbon price would not have any effect on the firm's cost and the final effect is simply the output scarcity rent.

If $S_i \geq e_i^*$ we know for sure that firm i would benefit from an increase in p, i.e., the scarcity rents would be large enough to overcompensate the additional cost. On the other hand, if $S_i < e_i^*$, in general we cannot tell which effect prevails at this level of generality. Anyway, since the final effect is strictly positive when $e_i^* = S_i$, by continuity we can assert that there is some interval of S_i such that firm i's profit increases with p even if the firm is a net buyer of permits (or has to pay a tax for some of its emissions). Recall that this event is discarded in monopoly as the output scarcity rent is absent. Note that this result is consistent with the main result in Hintermann (2011), according to which the threshold of free allocation beyond which the firm profits from a carbon price increase is below full allocation.[7]

2.2 Stackelberg

Consider now that there is a leader (firm 1) and a follower (firm 2) in the output market. The aim is to find out how different positions in the market determine the ability of a firm to capture scarcity rents. The follower's FOC is

$$P + \frac{dP}{dX} x_2 - \frac{\partial TC_2^*}{\partial x_2} = 0 \,, \tag{11}$$

[7] Note, anyway, that there is not a complete equivalence with Hintermann´s result as in their model there is a firm that enjoys market power both in the output and the permit market.

which implicitly gives the reaction function $x_2^R(x_1, p)$. Differentiating (11) and rearranging, we conclude that the follower's output is decreasing in the leader's output and the carbon price:[8]

$$\frac{\partial x_2^R}{\partial x_1} = \frac{-\dfrac{dP}{dX}}{2\dfrac{dP}{dX} - \dfrac{\partial^2 TC_2^*}{\partial x_2^2}} < 0, \qquad \frac{\partial x_2^R}{\partial p} = \frac{\dfrac{\partial^2 TC_2^*}{\partial x_2 \partial p}}{2\dfrac{dP}{dX} - \dfrac{\partial^2 TC_2^*}{\partial x_2^2}} < 0. \tag{12}$$

The leader's FOC is

$$P(x_1 + x_2) + \frac{dP}{dX} x_1 \left(1 + \frac{\partial x_2^R}{\partial x_1}\right) - \frac{\partial TC_1}{\partial x_1} = 0, \tag{13}$$

which implicitly determines the leader's optimal output as a function of the carbon price, $x_1^*(p)$. By differentiating (13), we conclude that the leader's output supply is also decreasing in p:

$$\frac{dx_1^*}{dp} = \frac{\dfrac{\partial^2 TC_1^*}{\partial x_1 \partial p}}{\dfrac{dP}{dX}\left(2 + \dfrac{\partial x_2^R}{\partial x_1}\right) - \dfrac{\partial^2 TC_1^*}{\partial x_1^2}} < 0. \tag{14}$$

Equations (12) and (14) show how the leader and the follower react to a carbon price increase. While the follower only takes into account the effect of its own output on the output price, the leader incorporates, not only its own, but also the follower's. This tends to make the denominator of (14) smaller in absolute value and, hence, the whole expression greater in absolute value, i.e., the leader's output tend to be more sensitive to the carbon price than the follower's.

Using the equilibrium output values we can express the profit of both firms solely as a function of the carbon price. Using the envelope theorem we obtain

---

[8] The denominator of both ratios is negative if the second order conditions hold. The same applies to the denominator of (14) in the case of the leader.

$$\frac{d\Pi_1^*}{dp} = \underbrace{S_1}_{SR_1^G} + \underbrace{\frac{dP}{dX}\frac{\partial x_2^R}{\partial p} x_1^*}_{SR_1^x} - e_1^*, \qquad (15)$$

$$\frac{d\Pi_2^*}{dp} = \underbrace{S_2}_{SR_2^G} + \underbrace{\frac{dP}{dX}\frac{dx_1^*}{dp} x_2^*}_{SR_2^x} - e_2^*, \qquad (16)$$

where we see the same qualitative effects as in the Cournot model: two components of the scarcity rents, SR^S and SR^x, and the marginal cost effect, and the resulting sign is undetermined. Note that the effect of a price increase on the follower's output has two components: a direct one and an indirect one through the leader's output. Formally, $\frac{dx_2^*}{dp} = \frac{\partial x_2^R}{\partial p} + \frac{\partial x_2^R}{\partial x_1}\frac{dx_1^*}{dp}$. Nevertheless, the latter effect is already accounted for in the leader's optimising process and hence only the former matters to determine the leader's scarcity rent.

Direct comparison of (15) and (16) shows that $SR_1^x \geq SR_2^x \Leftrightarrow \varepsilon_{x_2^R, p} \geq \varepsilon_{x_1^*, p}$, i.e. the relative size of the output scarcity rent depends again on the elasticities, but what matters for the leader is the elasticity of its equilibrium output, while for the follower it is the elasticity of its reaction function. The rest of the discussion presented in the Cournot case basically applies to the Stackelberg model.

The main conclusion that we can draw from (15) and (16) is that, unlike the Cournot case, the conditions under which a price increase is profit-enhancing are different for both firms. The reason is that their reactions to a price increase, given in (12) and (14), are different and, therefore, it may be the case that an increase in the carbon price causes the profit of one firm to increase and the other to decrease. To gain more accurate insights, we explore a specific case in the next section.

3. A Separable Function

3.1. Basic elements

Assume that production and abatement costs are separable in the following way. The production cost of firm i is given by cx_i, where c is a constant marginal cost. Each unit of output generates r units of pollution, where $r > 0$ is a constant coefficient of pollution intensity (the gross emissions of firm i are given by rx_i). By undertaking abatement activities, firms can reduce their flow of pollution. Let us denote as $q_i \geq 0$ the amount of emissions abated by firm i. Thus, net emissions are given by $e_i = rx_i - q_i$. Following Sartzetakis (1997), we assume the following quadratic abatement cost function (AC), which is common to both firms:

$$AC(q_i) = q_i(d + tq_i), \qquad d, t > 0. \tag{17}$$

The inverse output demand function is linear: $P(X) = a - bX$. Assume that both firms initially receive an equal allocation of free permits (or a tax exemption), $S_1 = S_2 = S$, and denote as y_i the amount of permits that firm i buys (if $y_i > 0$) or sells (if $y_i < 0$) in the market, which is given by

$$y_i = e_i - S = rx_i - q_i - S. \tag{18}$$

In other words, $e_i = y_i + S$, i.e., net emissions must be covered by permits that either come from the free allocation or are bought in the market. Firm i's total cost function can be written as

$$TC_i(x_i, e_i) = cx_i + (rx_i - e_i)(d + t(rx_i - e_i)) + p(e_i - S). \tag{19}$$

Solving the third stage of the game, we get optimal emissions:

$$e_i^*(x_i, p) = rx_i - \frac{p - d}{2t}, \qquad i = 1, 2, \tag{20}$$

and abatement is

$$q_i^*\left(p\right)=\frac{p-d}{2t}, \qquad i=1,2, \tag{21}$$

which, due to separability and cost symmetry, is independent of output and common for both firms. Using (20) in (18) and (19) we obtain the optimal traded permits and the corresponding minimized cost function:

$$y_i^*\left(x_i, p\right)=\frac{d-p}{2t}+rx_i-S\ , \tag{22}$$

$$TC_i^*\left(x_i, p\right)=x_i\left(c+pr\right)-\frac{\left(p-d\right)^2}{4t}-pS\ , \tag{23}$$

and (23) reveals that the marginal production cost is constant in output and increasing in the carbon price. The market value of S plays the role of a lump-sum cost reduction. Now we move on to the output stage.

3.2 Cournot

To ensure interior solution (with output, emissions and abatement being non-negative), we introduce the following assumption.

Assumption 1. *The price of permits is bounded in the following way:* $d \leq p \leq \overline{p}^C$ *where*

$$\overline{p}^C := \frac{2tr\left(a-c\right)+3bd}{2tr^2+3b}.$$

The lower bound for p prevents abatement from being negative (see (21)). Note that d is the marginal cost of abatement at $q=0$. If the carbon price is lower than the cost of the first unit of abatement, it is never profitable to abate, since buying permits (or paying the tax) is a cheaper option. The upper bound prevents emissions from being negative, which implies that output is also positive.[9]

From the FOCs we get the equilibrium output:

[9] If net emissions and abatement are nonnegative, gross emissions must also be nonnegative, i.e. $rx_i \geq 0$, which implies $x_i \geq 0$.

$$x_i^* = x_{-i}^* = \frac{a-c-rp}{3b}. \quad (24)$$

The equilibrium profits are also constant across firms and given by $\Pi_i^* = \left(a - 2bx_i^*\right)x_i^* - TC_i^*\left(x_i^*, p\right)$. By differentiation, we get the particular version of (10):

$$\frac{\partial \Pi_i^*(p)}{\partial p} = \underbrace{S}_{SR_i^G} + \underbrace{\frac{r}{3}x_i}_{SR_i^x} - \underbrace{\left(rx_i - \underbrace{\frac{p-d}{2t}}_{q_i^*}\right)}_{e_i^*}. \quad (25)$$

The first term in (25) is the grandfathering scarcity rent, the second is the output scarcity rent and the third (the whole parenthesis) is the cost effect, which equals net emissions. We can get some useful intuitions by simple inspection of (25).

First, by making S large enough, it's always possible to make a firm willing to bear a higher carbon price thanks to the grandfathering scarcity rent, as any firm would benefit by holding a large amount of an asset that is becoming scarcer (and thus more expensive) in the market.

Now drop the grandfathering effect by setting $S = 0$ in (25) (i.e., permits are sold in an auction instead of grandfathering or there is no tax exemption). There are still two positive effects, the combination of which may cause the firm to benefit from an increase in the carbon price. The first is the output scarcity rent and the second is the firm's ability to react by means of abatement (the second term in the parenthesis). If there was not an available abatement technology or it was prohibitively expensive,[10] then the right-hand side of (25) would collapse to $-\left(2r/3\right)x_i$, whose sign is unambiguously negative. The economic consequence of this result is that the output scarcity rent by itself would never be enough to fully compensate the cost effect of a higher carbon price.[11]

[10] This can be seen by making t arbitrarily large in (25).

[11] This conclusion is sensitive to the linear demand assumption. See the "conclusions and discussion" section.

We can use the equilibrium values of output and emissions to write profit in terms of the carbon price:

$$\Pi_i^*(p) = \frac{(a-c-pr)^2}{9b} + \frac{(p-d)^2}{4t} + pS \,. \tag{26}$$

The main features of this function and their economic consequences are summarised in Proposition 1:

Proposition 1. *Under assumption* 1, $\Pi_i^*(p)$ *is a strictly convex function of* p *with a global minimum at* $\hat{p}^C := \frac{4tr(a-c)+9b(d-2tS)}{4tr^2+9b}$, *where* $d < \hat{p}^C < \overline{p}^C$. *Therefore,* $\Pi_i^*(p)$ *is decreasing for* $p < \hat{p}^C$ *and increasing for* $p > \hat{p}^C$.

According to Proposition 1, the profit function is U-shaped and there is a critical value of the carbon price, $\hat{p}^C$, below which the negative effect dominates, i.e., an increase of the carbon price will reduce the firms' profit, whereas above it further increments of the price will generate more than enough scarcity rents to offset the negative effect.

The shape of these functions is determined by the behaviour the components of (25) with respect to p. According to (24), output is decreasing in p and so is the size of the output scarcity rent, while the grandfathering scarcity rent is constant in p. Combining (20) and (24) we conclude that the cost effect (determined by e_i^*) is a decreasing function of p. This is due to the ability of the firm to adapt by reducing output (and emissions) and increasing abatement. It turns out that the latter effect dominates the former, which gives the profit function a convex shape.

3.3 Stackelberg

Assume that firms 1 and 2 are a leader and a follower respectively. In this case, we need to impose Assumption 2 to ensure interior solution. [12]

Assumption 2. *The price of permits is bounded in the following way:* $d \le p \le \overline{p}^S$ *where*

$$\overline{p}^S := \frac{2bd + rt(a-c)}{2b + tr^2}. \tag{27}$$

By standard methods, we obtain the equilibrium outputs:

$$x_1^* = \frac{a-c-rp}{2b}, \tag{28}$$

$$x_2^* = \frac{a-c-rp}{4b}. \tag{29}$$

From (28) and (29), we conclude that the leader's output is twice that of the follower. Using these expressions we obtain the equilibrium profits in terms of p and, by differentiation, we obtain the effect of the carbon price on profits:

$$\frac{\partial \Pi_i^*}{dp} = \underbrace{S}_{SR_i^G} + \underbrace{\frac{r}{2} x_i^*}_{SR_i^x} - \underbrace{\left(r x_i^* - \frac{p-d}{2t} \right)}_{-e_i^*}, \tag{30}$$

which looks similar to (25) and qualitatively the same effects are present. The grandfathering scarcity rent and the abatement effect are identical as in the Cournot model. Once again, the output scarcity rent by itself cannot compensate for the cost effect due to a higher carbon price. Also, the positive abatement effect is increasing in p, and so the higher the carbon price the more the firms can benefit by doing abatement to adapt themselves to the market conditions.

As a difference from the Cournot case, the output scarcity rent that accrues to each firm represents a larger proportion of its own output ($r/2$ instead of $r/3$). Another

[12] In this case, the upper bound is set at the point at which the emissions of the follower become zero, which implies that the rest of relevant variables are non-negative.

difference is due to the fact that the leader produces twice as much as the follower, and thus, it enjoys more output scarcity rents, but its gross emissions are also bigger than the follower's. Simple manipulation of (30), together with (28) and (29), gives

$$\frac{\partial \Pi_1^*}{dp} - \frac{\partial \Pi_2^*}{dp} = -\frac{r}{2}\left(x_1^* - x_2^*\right) = -\frac{r\left(a-c-rp\right)}{8b} < 0, \tag{31}$$

where the inequality always holds under interior solution. Therefore, a rise in the carbon price will always benefit more (or harm less) the follower than the leader. The reason lies in the output difference: since the leader produces more than the follower, it also pollutes more and its cost is more sensitive to the carbon price. The impact of p on both firms' profit is summarised in the following proposition:

Proposition 2. $\Pi_1^*(p)$ *and* $\Pi_2^*(p)$ *are strictly convex functions of* p *with a global minimum at* $\hat{p}_1^S$ *and* $\hat{p}_2^S$ *respectively, with* $d < \hat{p}_2^S < \hat{p}_1^S$.

According to Proposition 2, the minima of the profit functions are ordered such that $\hat{p}_2 < \hat{p}_1$; i.e., the follower reaches a minimum for a lower price than the leader. Hence, if $p < \hat{p}_2$ both firms are situated in the decreasing part of their profit functions (and so they would prefer that the price decreases). If, instead, $\hat{p}_2 < p < \hat{p}_1$, the follower is situated in the increasing part (and so will benefit from a price increase), whereas the leader is still in the decreasing part (and therefore will still prefer the price to decrease). So, one important novelty of the Stackelberg model with respect to Cournot is the fact that both firms can have different interests regarding the evolution of p.

4. Firms' agreement on tougher policies

It is a common belief that firms will generally oppose tougher environmental policies as they will make them worse off. In practice, this opposition can be one of the main hurdles for policy makers (see, e.g. Switzer, 1997). But, as discussed in the introduction, some authors have shown that this is not always the case as, under some circumstances, a tougher policy could increase, rather than decrease, firms' profits. Our results point in the same direction due to the existence of scarcity rents. In this section we explore the question of how the existence of scarcity rents can make the firms willing to accept a tougher climate policy. We pay particular attention to the case in which both firms are simultaneously willing to accept a higher carbon price as this seems the most favourable situation for policy makers to introduce a tougher carbon policy. We call the parameter range in which this event takes place the "agreement region".

To get sharper results about this question we focus on the separable case introduced in Section 3, although the qualitative insights we obtain could be extended to a more general setting. We have shown that, both in the Cournot and the Stackelberg cases, for each firm there is a threshold below which it prefers the carbon price to decrease and above which it prefers an increase. The comparison of these thresholds is crucial to determine the firms' willingness to accept a tougher policy.

4.1 Cournot vs. Stackelberg

In the Cournot model, according to Proposition 1, the threshold value is $\hat{p}^C$, which splits the range of possible values for p into two non-empty regions, that we call C-I:= $[d, \hat{p}^C)$ and C-II:=$(\hat{p}^C, \overline{p}^C]$. The profit of both firms is decreasing in p in the first region and increasing in the second. Therefore, the agreement region in this case is C-II.

Things are somewhat different in the Stackelberg case. From Proposition 2, we know $\hat{p}_2^S < \hat{p}_1^S$, which means that the follower reaches the threshold value for a lower value of p than the leader does. As it is shown in Figure 1, this can give rise to three different regions. In region S-I:=$[d, \hat{p}_2^S)$, the profit of both firms is decreasing in p.

In region S-II:$=(\hat{p}_2^S, \hat{p}_1^S)$, the profit of the leader is still decreasing while the follower's is increasing. Finally, in region S-III:$=(\hat{p}_1^S, \overline{p}_1^S]$ the profit of both firms is increasing in p. So, the agreement region is S-III. Proposition 3 compares the relevant thresholds for both models.

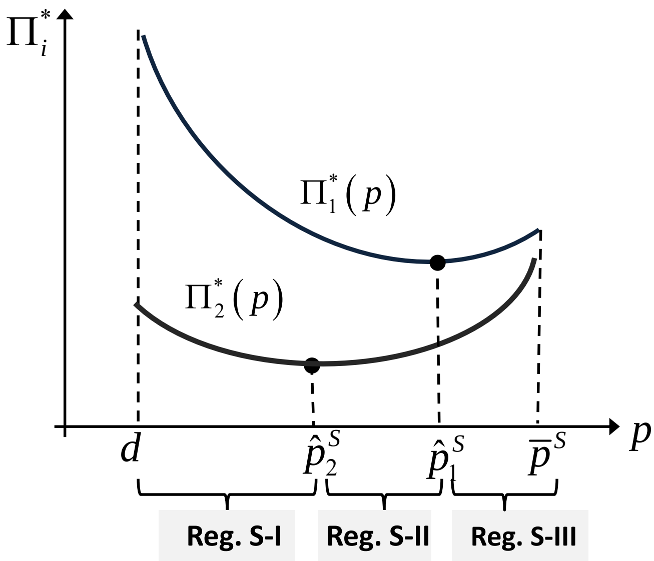

FIGURE 1: Equilibrium profits as a function of *p* in the Stackelberg model

Proposition 3. *The critical values of the carbon price in the Cournot and the Stackelberg model are ordered in the following way:* $\hat{p}_2^S < \hat{p}^C < \hat{p}_1^S \leq \overline{p}^S < \overline{p}^C$.

According to Proposition 3, $\hat{p}_2^S < \hat{p}^C < \hat{p}_1^S$, which means that a Cournot firm reaches the threshold value later (for a higher price) than a Stackelberg follower but sooner than a Stackelberg leader. Moreover, the last three inequalities in Proposition 3 imply that region S-III is strictly contained in region C-II, i.e., the agreement region is larger under Cournot than under Stackelberg competition. We conclude that under a leader-follower relationship it is less likely than in a symmetric setting that both firms are simultaneously willing to accept a higher carbon price.

Whatever the market structure, one natural question is how large the agreement region is, or, in other words, how likely it is to fall within this region. Consider the Stackelberg case. Region S-III is delimited by two threshold values for p. First, $\hat{p}_1^S$, which is the price above which it is profitable, not only for the follower, but also for the leader to face a higher price. The second threshold is the upper bound, $\overline{p}^S$, which is the highest value of the price compatible with an interior solution. The size of region III is thus given by the difference between these two thresholds, which can be computed as

$$\overline{p}^S - \hat{p}_1^S = \frac{4btS}{2b+tr^2}, \tag{32}$$

and so the size of region S-III depends positively on the number of free permits received by the firms, as well as the slope of the demand curve, b, and the abatement cost parameter t, whereas it depends negatively on the emissions intensity parameter, r. In the next subsection we focus on the role of grandfathering.

4.2 The role of grandfathering[13]

Consider first the Cournot model. For convenience, we define the following threshold:

$$\tilde{S}^C := \frac{2r\left(a-c-dr\right)}{9b}.$$

Proposition 4. *In the Cournot model, under Assumption* 1*, the following results hold:*

a) As S increases, $\hat{p}^C$ decreases, which implies that the size of region C-I decreases and that of region C-II increases.

[13] In the case of carbon tax, a similar discussion can made be around a tax exemption, but the grandfathering story seems more relevant in practice as there is currently a tendency to move from grandfathering to auctioning (e.g. in the EU ETS).

b) *For any value* $S \geq \tilde{S}^C$ *, region C-I disappears.*

c) *The size of region C-II is strictly positive for* $S = 0$ *.*

Increasing the number of free permits, S, shifts the lower bound of region C-II to the left while the upper bound price remains the same. Therefore, region C-I shrinks and region C-II gets larger, which implies that the chances for agreement increase. Moreover, Proposition 4 shows that region C-I disappears if S is large enough. The main consequence is that the more free permits the firms own, the more likely they are to be willing that the carbon price increases. The reason is that the existence of free permits makes permit purchasing less costly. Moreover, if S is large enough it opens the way for obtaining positive revenues by selling some permits. Nevertheless, result c) in the proposition implies that, even without grandfathering, there is a positive range such that both firms prefer the carbon price to increase.

We now perform a similar exercise for the Stackelberg case. Define the following threshold value for S:

$$\tilde{S}^S := \frac{r\left(a - c - dr\right)}{8b}. \tag{33}$$

Lemma 1. *In the Stackelberg model, under Assumption 2, the following results hold:*

a) *If* $0 < S < \tilde{S}$ *, then* $d < \hat{p}_2 < \hat{p}_1 < \overline{p}^S$ *.*

b) *If* $\tilde{S} < S < 2\tilde{S}$ *, then* $\hat{p}_2 < d < \hat{p}_1 < \overline{p}^S$ *.*

c) *If* $S > 2\tilde{S}$ *, then* $\hat{p}_2 < \hat{p}_1 < d < \overline{p}^S$ *.*

d) *If* $S = 0$ *, then* $d < \hat{p}_2 < \hat{p}_1 = \overline{p}^S$ *.*

Proposition 5. *In the Stackelberg model, under Assumption 2, the following results hold:*

a) *If* $0 < S < \tilde{S}^S$ *, regions S-I, S-II and S-III are non-empty.*

b) *If* $\tilde{S}^S < S < 2\tilde{S}^S$ *, region I disappears and region II is delimited by* $d < p < \hat{p}_1^S$ *.*

c) If $S > 2\tilde{S}^S$ *, regions I and II disappear and region III is defined by the entire feasible range,* $[d, \overline{p}^S]$.

d) If $S = 0$ *, region S-III disappears.*

The consequences of Lemma 1 and Proposition 5 are the following. The threshold values $\hat{p}_1^S$ *and* $\hat{p}_2^S$ decrease with S , which implies that, for each firm, there is a wider range such that its profit is increasing in p . This renders a similar conclusion as in the Cournot model: the chances of agreement increase with grandfathering. If the initial allocation is large enough, region I disappears, which implies that the follower is always interested in increasing p and, if it is even larger, both regions I and II disappear, which implies that both the leader and the follower are always willing to accept a higher carbon price. This is the most favourable case for making the carbon policy tougher.

There is an important qualitative difference with respect to the Cournot model: without grandfathering (i.e., $S = 0$) the size of the agreement region decreases to the extent that it disappears because a price increase is never profitable for the leader although it can be for the follower. The policy implication is that, if the output market is characterised by Stackelberg competition and there is no grandfathering, it is unlikely that the firms are willing to agree on a more stringent policy.

4.3. Parameter asymmetries in. the Stackelberg model

In the previous subsections we have assumed that both firms are fully symmetric in terms of their cost functions and the initial allocation they receive. In the Cournot case, moreover, they are also symmetric regarding their role in the market. In the Stackelberg model, although they are symmetric in terms of the parameters there is an asymmetry in their role as one acts as a leader and the other as a follower.

As a sensitivity analysis, in this subsection we consider the possibility that firms are asymmetric in terms of cost and/or initial permit endowment. In the Cournot case, since we start from a fully symmetric situation, it is rather straightforward to conclude that introducing any asymmetry between the firms will make their interests diverge and the chances for agreements will decrease. So, we focus on the Stackelberg case, in which the results are less obvious as we start from a situation that is already asymmetric in nature.

We denote the production cost of firm i as $c_i x_i$, where c_i is a firm-specific unit cost parameter. Analogously, firm *i*'s abatement cost function is given by:

$$AC_i\left(q_i\right)=q_i\left(d_i+t_i q_i\right), \qquad i=1,2. \tag{34}$$

Each firm receives an initial free endowment of permits, S_i, which is not necessarily constant across firms. Proceeding as in the basic case, we obtain the optimal amounts of emissions, abatement and purchase of permits for each firm in the emissions stage:[14]

$$e_i^*\left(x_i,p\right)=\frac{d_i-p}{2t_i}+rx_i, \tag{35}$$

$$q_i^*\left(p\right)=\frac{p-d_i}{2t_i}, \tag{36}$$

$$y_i^*\left(x_i,p\right)=rx_i-\frac{p-d_i}{2t}-S_i, \tag{37}$$

and, moving on to the output stage, we can compute the equilibrium levels of output:

$$x_1^*=\frac{a+c_2-2c_1-rp}{2b}, \tag{38}$$

$$x_2^*=\frac{a+2c_1-3c_2-rp}{4b}. \tag{39}$$

[14] Unlike the other parameters, we assume that the emissions intensity parameter, r, is common to both firms; i.e., $r_1=r_2=r$. There are two reasons for this simplification. First, the sensitivity analysis results related to these parameters are unclear and so we do not gain any valuable insight by exploring them. Second, the sign of some equilibrium values for some of the key variables are affected by the terms $2r_1-r_2$ and/or $3r_1-2r_2$ and this fact forces us to keep the asymmetry between these parameters bounded so as to avoid meaningless results.

To investigate the likelihood of agreement, we proceed by analysing the effect of different parameters on the size of region S-III. Due to the larger number of parameters, by choosing the right combination of them we could generate almost any imaginable case. Hence, we need to delimit the range of possibilities so as to avoid meaningless results. For this reason, we introduce the following assumptions:

Assumption 3: $d_1, d_2 < p < \overline{p}^{S-2}$, *where* $\overline{p}^{S-2}$ is the value of p such that $e_2^* = 0$.

Assumption 4: The parameters of the model are such that $e_1^* > e_2^*$.

Assumption 5: The parameters of the model are such that $\hat{p}_2^S < \hat{p}_1^S$.

Apart from guaranteeing interior solution, these assumptions ensure that the leader will still be the one who produces a larger amount of output and emissions. Hence, the follower will still be the one who finds it profitable to pollute zero for a lower value of p and such a value determines the upper bound for the interval that is compatible with an interior solution, $\overline{p}^{S-2}$ (where "$S-2$" stands for "Stackelberg, case 2"). Accordingly, it is easier for the follower than it is for the leader to benefit from a price increase.

Under these assumptions, region S-III is still delimited by the leader's critical price, call it $\hat{p}_1^{S-2}$, and the upper bound $\overline{p}^{S-2}$ and hence its size increases if $\overline{p}^{S-2}$ increases and/or $\hat{p}_1^{S-2}$ decreases. Proposition 6 summarises how the size of this region depends on the parameters of the model and Table 1 presents a taxonomy of all the relevant effects.

Proposition 6. *In the Stackelberg case, under assumptions 1, 2 and 3, the size of region S-III increases in the following cases:*

a) *If the leader's marginal production cost,* c_1*, increases or the follower's marginal production cost,* c_2*, decreases.*

b) *If the parameter of the linear term in the abatement cost function decreases for the leader (*d_1*) or increases for the follower (*d_2*).*

c) *If the parameter of the quadratic term in the leader's abatement cost function,* t_1*, decreases (provided the number of free permits is moderate) or the equivalent follower's parameter,* t_2*, increases.*

d) *If the number of free permits received by the leader,* S_1*, increases, regardless of the free permits received by the follower .*

Effects on **Thresholds**	***Changes in model parameters***							
	c₁	***c₂***	***d₁***	***d₂***	***t₁***	***t₂***	***S₁***	***S₂***
$\Delta \overline{p}^{S-2}$	+	-	0	+	0	+	0	0
$\Delta \hat{p}_1^{S-2}$	-	+	+	0	+ (*)	0	-	0
$\Delta\left(\overline{p}^{S-2} - \hat{p}_1^{S-2}\right)$	+	-	-	+	- (*)	+	+	0

Table 1. Summary of sensitivity analysis results.

(*) For a moderate value of S_1.

Increasing the leader's production cost or reducing the follower's production cost tends to erode the leader's advantage with respect to the follower in the output market, which has the effect of making the firms more symmetric in a certain sense. The more symmetric the firms are, the more aligned their interests will be and hence it is more likely that they agree. Increasing c_1 has a twofold effect. On the one hand, $\overline{p}^S$ grows because the follower's output increases, which makes it less likely for firm 2 to decide not to emit at all (in other words, the range of prices under which there is an interior solution widens). On the other hand, $\hat{p}_1^S$ decreases as, due to the higher cost, firm 1 tends to produce less and to emit less and hence its total cost will be less sensitive to an increase in the price of permits. Both of these effects tend to enlarge the agreement region. Just the opposite occurs when c_2 increases. Firm 1 tends to produce more and pollute more and hence its cost becomes more sensitive to an increase in the price of permits (which increases the value of $\hat{p}_1^S$), whereas the follower tends to produce less and to reach the point where it finds it profitable to stop polluting sooner ($\overline{p}^S$ decreases), which reduces the size of the agreement region.

The abatement cost parameters (d_i and t_i) are only relevant for the own firm, but not for its rival. Both d_2 and t_2 are irrelevant in determining the value of $\hat{p}_1^S$. However, increasing either of them enlarges the relevant feasible range because the follower's abatement cost increase, which makes it less likely to reach the point where it pollutes zero. The corresponding parameters for firm 1 are immaterial in determining the value of $\overline{p}^S$, their only relevant effect being on $\hat{p}_1$. Assuming a moderate value of the leader's initial endowment of permits, any increase in d_1 and t_1 makes the leader's abatement cost higher, which makes firm 1 become more sensitive to increases in the price of permits.

Finally, the initial allocation of permits is irrelevant for the upper bound $\overline{p}^S$, as it represents simply a fixed term in the cost (and the profit) function and so the optimal decisions are not affected. The value of a firm's profits is affected by its own endowment (not the rival's) and hence only S_1 is relevant in determining the size of region S-III. When the leader's free endowment increases, its cost becomes less sensitive to an increase in the price of permits and it will hence be more receptive to the idea of facing a higher carbon price.

5. Conclusions and discussion

We have studied the creation of scarcity rents for oligopolistic firms due to the existence of a carbon price and, more specifically, how these rents respond to a price increase. Along with a higher compliance cost, a carbon price increase can generate scarcity rents in two ways: firstly, by restricting output and pushing up its price, and secondly, when the firms are endowed with an initial allocation (in the form of grandfathering or a tax exemption), a higher carbon price makes such an allocation more valuable.

We have demonstrated that the extent to which so-called output scarcity rents can be obtained by a specific firm increases with the elasticity of its rival's output to the carbon price. The reason is that the effect of own output variation cannot be profitable in equilibrium.

A leadership position tends, ceteris paribus, to make a firm produce more, so its cost becomes more sensitive to a carbon price increase. As a consequence, a leader is less prone to be willing to face a higher price and thus to accept a tougher carbon policy. Therefore, if the firms are otherwise symmetric, the existence of a leader-follower relationship makes it more difficult to reach a consensus on a more stringent policy. In a specific example we have shown that the agreement region can shrink to such an extent that it can disappear.

Another policy implication is that exempting a part of total emissions (e.g. by means of grandfathering) seems a crucial device to make firms willing to accept a tougher carbon policy. In the case of Stackelberg competition (with otherwise symmetric firms) this effect may be particularly important, as the existence of grandfathering is actually a necessary condition for an agreement region to exist. The greater the amount of exempt emissions (particularly for firms that enjoy market power) the more willing firms will be and, in the case of a Stackelberg setting, it is the leader's initial allocation that matters. The European Union is reducing the use of grandfathering and increasing the use of auctioning to distribute emission permits.[15] One of the hurdles that this policy change may find is the opposition of firms.

Firms' receptiveness to tougher policies appears to be very sensitive to the cost asymmetries between them. In general terms, the more asymmetric the firms are, the more difficult it is to reach a consensus.

To keep our analysis simple and intuitive, we have intentionally kept some simplifying assumptions that can merit some discussion. One simplification we have adopted is to assume that there are only two firms. In the Appendix we present the extension of our analysis to an arbitrary number of firms and show that all the central results are still valid.

Also, in our specific example we have assumed a linear demand. Although this is not fundamental for the central messages, it has the implication that output scarcity rent by itself cannot be high enough to fully compensate the cost effect of a higher carbon price. Under an iso-elastic demand the cost pass-through can be more than complete and the output scarcity rent could outweigh the increase in compliance costs.

To focus on the leader-follower competition, in the Stackelberg model we have initially kept the firms otherwise symmetric. Even in our sensitivity analysis (Subsection 4.3) we have kept a certain degree of symmetry to ensure that the order of the relevant thresholds is not altered. The reason is that, by changing the parameters of the model in the right direction, we could generate almost any imaginable situation. Specifically, we have assumed that the emission intensity is constant across firms. Without this assumption it is not necessarily true that the leader's cost is more sensitive to the carbon price than the follower's.

Some authors have pointed out the possibility that some firms enjoying market power could manipulate the carbon price up. See, among others, Misiolek and Elder (1989),

---

[15] The 2008 revised European Emission Trading Directive established the mandate that auctioning is to be the default method for allocating allowances as a fundamental change for the third trading period, starting in 2013. See, e.g. Alvarez and André (2015).

Von der Fehr (1993), Sartzetakis (1997, 2004), Hintermann (2011, 2015) or Ehrhart *et al.* (2008). We have not explicitly addressed this possibility as we have taken the carbon price as exogenous whereas in most of the literature on price manipulation market power is assumed in the permit market.[16] Nevertheless, it is possible to interpret our results in terms of generation of incentives for price manipulation.[17] In this respect, our results show that the findings by, e.g. Hintermann (2011, 2015) are somewhat robust to the choice of competitive setting.

Finally, we have not addressed welfare analysis. One can argue that the generation of scarcity rents will make firms better off but it will also make consumers worse off. Nevertheless, a fully-fledged welfare analysis would also require a consideration of the effect of policy on environmental quality, which is beyond the scope of this paper.

Funding

This work was supported by the Spanish Ministry of Economy and Competitiveness and Development Fund, ERDF [grants ECO2012-39553-C04-01, ECO2015-70349-P

Acknowledgements

Suggestions by Michael Finus were extremely useful. We also appreciate comments and discussion by two anonymous referees, Francisco Cabo, Santiago Rubio, the members of the Department of Business of the University of the Balearic Islands and the participants in the Madrid Environmental Economics Seminar (MEES) and the VI Conference of the Spanish and Portuguese Association of Resource and Environmental Economics (AERNA).

References

[16] One exception is Ehrhart *et al.* (2008), who also take the carbon price as exogenous.

[17] This interpretation is more explicitly addressed in the working paper version of this article (see André and De Castro 2015)

Alvarez, F. and André, F.J. (2015) Auctioning vs. Grandfathering in Cap-and-Trade Systems with Market Power and Incomplete Information, *Environmental and Resource Economics*, **62**, 973-906.

André, F.J., González, P. and Porteiro, N. (2009) Strategic quality competition and the Porter Hypothesis, *Journal of Environmental Economics and Management*, **57**, 182-194.

André, F.J. and De Castro, L.M. (2015) Scarcity Rents and Incentives for Price Manipulation in Emissions Permit Markets with Stackelberg Competition, Working Paper MPRA (No. 61770) University Library of Munich, Germany.

Convery, F. J. (2009) Origins and development of the EU ETS, *Environmental and Resource Economics*, **43**, 391-412.

De Feo, G., Resende, J. and Sanin, M.E. (2013) Emission permit trading and downstream strategic market interaction, *The Manchester School*, **81**, 780-802.

Ehrhart, K.M, Hoppe, C. and Löschel, R. (2008) Abuse of EU Emissions Trading for Tacit Collusion, *Environmental and Resource Economics*, **41**, 347-361.

Elkins, P. and Baker, T. (2001) Carbon taxes and carbon emissions trading, *Journal of Economic Surveys*, **15**, 325-376.

Ellerman, A.D., Convery, F.J. and de Perthuis, C. (2010) *Pricing Carbon: the European Emissions Trading Scheme*. Cambridge University Press, Cambridge.

Eshel, D.M.D. (2005) Optimal allocation of tradable pollution rights and market structures *Journal of Regulatory Economics*, **28**, 205-223.

Fullerton, D. and Metcalf, G.E. (2001) Environmental controls, scarcity rents, and pre-existing distortions, *Journal of Public Economics*, **80**, 249-267.

Goulder, L. H., and Schein, A. R. (2013) "Carbon taxes versus cap and trade: a critical review", *Climate Change Economics*, **4**.

Hahn, R. (1984) Market Power and Transferable Property Rights, *Quarterly Journal of*

Economics, **99**, 753–765.

Hintermann, B. (2011) Market Power, Permit Allocation and Efficiency in Emission Permit Markets, *Environmental and Resource Economics*, **49**, 327-349.

Hintermann, B. (2015) Market Power in Emission Permit Markets: Theory and Evidence from the EU ETS, *Environmental and Resource Economics*. Published on line 07 July 2015. DOI 10.1007/s10640-015-9939-4.

Kalkuhl, M. and Brecha, R.J. (2013) "The Carbon Rent Economics of Climate Policy", *Energy Economics*, **39**, 89-99.

MacKenzie, I.A. and Ohndorf, M. (2012) "Cap-and-trade, Taxes and Distributional Conflict", *Journal of Environmental Economics and Management*, **63**, 51-65.

Meunier, G. (2011) Emission Permit Trading Between Imperfectly Competitive Product Markets, *Environmental and Resource Economics*, **50**, 347-364.

Misiolek, W. and Elder, H. (1989) Exclusionary manipulation of markets for pollution rights, *Journal of Environmental Economics and Management*, **16**, 156–66.

Mohr, R.D. and Saha, S. (2008) Distribution of Environmental Costs and Benefits, Additional Distortions, and the Porter Hypothesis, *Land Economics*, **84**, 689-700.

Montero, J.P. (2009) Market Power in Pollution Permit Markets, *The Energy Journal*, **30**, 115-142.

Newell, R. G., Pizer, W.A. and Raimi, D. (2013) Carbon Markets 15 Years after Kyoto: Lessons Learned, New Challenges, *The Journal of Economic Perspectives*, **27**, 123-146.

Sartzetakis, E.S. (1997) Tradeable Emission Permits Regulations in the Presence of Imperfectly Competitive Product Markets: Welfare Implications, *Environmental and Resource Economics*, 9, 65-81.

Sartzetakis, E.S. (2004) On the Efficiency of Competitive Markets for Emission Permits, *Environmental and Resource Economics*, 27, 1-19.

Sijm, J., Neuhoff, K., and Chen, Y. (2006) CO2 cost pass-through and windfall profits in the power sector *Climate Policy*, 6, 49-72.

Smale, R., Hartley, M., Hepburn, C., Ward, J. and Grubb, M. (2006) The impact of CO2 emissions trading on firm profits and market prices, *Climate Policy*, 6, 31-48.

Switzer, J. V. (1997) Green backlash: The history and politics of the environmental opposition in the US. Lynne Rienner Publishers.

Tietenberg, T. (2010) “Cap-and-Trade: The Evolution of an Economic Idea, *Agricultural and Resource Economics Review*, 39, 359–367.

Von der Fehr, N.H. (1993) Tradeable emissions rights and strategic interaction. *Environmental and Resource Economics*, 3, 129–151.

APPENDIX

Proof of Proposition 1

The equilibrium value for emissions can be obtained from equations (20) and (24). Equating this value to zero we conclude that emissions are positive under Assumption 1:

$$e_i^* = \frac{2tr\left(a-c-rp\right)-3b\left(p-d\right)}{6bt} \geq 0 \Leftrightarrow p \leq \overline{p}^C := \frac{2tr\left(a-c\right)+3bd}{3b+2tr^2} \qquad \text{(A.1)}$$

Using equations (23) and (24) together with the inverse demand function yields the following expression for the equilibrium profit:

$$\Pi^*_i\left(p\right) = \frac{4t\left(a-c-rp\right)^2 + 9b\left(p-d\right)^2 + 36bptS}{36bt},$$

which is strictly convex in p because the second derivative is positive. From the first derivative we get the critical price

$$\frac{\partial \Pi_i^*}{\partial p} \geq 0 \Leftrightarrow p \geq \hat{p}^C := \frac{4rt\left(a-c\right)+9bd-18btS}{9b+4r^2t}. \qquad \text{(A.2)}$$

By direct comparison , we conclude

$$\bar{p}^C - \hat{p}^C = \frac{6brt\left(a-c-dr\right)+18btS\left(3b+2r^2t\right)}{\left(3b+2r^2t\right)\left(9b+4r^2t\right)} > 0, \tag{A.3}$$

which is positive under Assumption 1 because all the parentheses are positive. To prove that $\left(a-c-dr\right)$ is positive, using (21) and the definition of abatement ($q_i = rx_i - e_i$), we conclude that, within the relevant range, $x_i^* > \frac{e_i^*}{r} > 0$. Using the expression for x_i^* given in (24), we conclude that $x_i > 0$ implies $a-c > rp$, and that this inequality, together with $d < p$ (Assumption 1), implies $a-c > dr$. QED.

Proof of Proposition 2

Using (28) and (29) in (20), we obtain the equilibrium values for emissions:

$$e_1^* = \frac{db + rt\left(a-c\right) - p\left(b+tr^2\right)}{2bt}, \tag{A4}$$

$$e_2^* = \frac{2bd + tr\left(a-c\right) - p\left(2b+tr^2\right)}{4bt}, \tag{A5}$$

By direct comparison we conclude that under Assumption 2, equilibrium emissions are nonnegative,

$$e_1^* > e_2^* \geq 0 \Leftrightarrow p \leq \bar{p}^S := \frac{2bd + rt\left(a-c\right)}{2b+tr^2}. \tag{A6}$$

and following the same reasoning as in the proof of Proposition 2, output must also be nonnegative. Using the equilibrium values of output and emissions, together with the expression of the inverse demand and the cost function (19) we obtain the equilibrium profits of both firms:

$$\Pi_1^*(p) = P(x_1^* + x_2^*)x_1^* - TC_1^*(x_1^*, p) = \frac{t(a-c-pr)^2 + 2b(p-d)^2 + 8btpS}{8bt},$$

$$\Pi_2^*(p) = P(x_1^* + x_2^*)x_2^* - TC_2^*(x_2^*, p) = \frac{t(a-c-pr)^2 + 4b(p-d)^2 + 16btpS}{16bt}.$$

The second derivative reveals that these functions are strictly convex. Differentiating them with respect to *p*, we conclude that they have respective minima at

$$Arg\min_p \Pi_1^*(p) \equiv \hat{p}_1^S = \frac{rt(a-c) + 2bd - 4btS}{2b + tr^2},$$

$$Arg\min_p \Pi_2^*(p) \equiv \hat{p}_2^S = \frac{rt(a-c) + 4bd - 8btS}{4b + tr^2},$$

and it follows straightforwardly that both $\hat{p}_1^S$ and $\hat{p}_2^S$ depend negatively on S.

Regarding the order of the thresholds, by direct comparison we conclude that $\hat{p}_1^S > \hat{p}_2^S \Leftrightarrow 2brt(a-c-dr+2rSt) > 0$; however, we have already proved $a-c-dr \geq 0$ in Proposition 1, which ensures that $\hat{p}_1^S > \hat{p}_2^S$. Moreover, using (A6) we also conclude that $\overline{p}^S = \hat{p}_1^S + \frac{4btS}{2b+tr^2} > \hat{p}_1^S$. Hence, we have that $\hat{p}_2^S < \hat{p}_1^S < \overline{p}^S$. QED.

Proof of Proposition 3

To prove the proposition it is enough to compare the corresponding expressions, compute the difference and check the sign.

$$\hat{p}_1^S - \hat{p}^C \Leftrightarrow \frac{brt(a-c-dr) + 2br^2t^2S}{(2b+r^2t)(9b+4r^2t)} > 0,$$

$$\hat{p}^C - \hat{p}_2^S \Leftrightarrow \frac{7brt(a-c-dr) + 14br^2t^2S}{(9b+4r^2t)(4b+r^2t)} > 0,$$

$$\overline{p}^C - \overline{p}^S = \frac{rbt(a-c-dr)}{(3b+2r^2t)(2b+r^2t)} > 0. \qquad \text{QED}$$

Proof of Proposition 4

The first part of the proposition results from deriving the expression for $\hat{p}^C$ given in (A.2) with respect to S. To prove the second part note that Region I disappears when $d \geq \hat{p}^C$, and using the expression for $\hat{p}^C$:

$$\hat{p}^C \leq d \Leftrightarrow \frac{4rt\left(a-c\right)+9bd-18btS}{9b+4r^2t} \leq d \Leftrightarrow S \leq \frac{2r\left(a-c-dr\right)}{9b} := \tilde{S} .$$

The third part follows immediately from (A.3). QED

Proof of Lemma 1

From Proposition 2 we know $\hat{p}_2^S < \hat{p}_1^S < \overline{p}^S$. To determine the relative position of d, first note that Assumption 2 implies $d < \overline{p}^S$ and hence we only have to check whether d is below $\hat{p}_2^S$, in the interval $\left(\hat{p}_2^S, \hat{p}_1^S\right)$ or in the interval $\left(\hat{p}_1^S, \overline{p}^S\right)$. By direct comparison, we conclude the following, which prove statements *b*) and *c*)*:*

$$\hat{p}_1^S > d \Leftrightarrow S < \frac{r\left(a-c-dr\right)}{4b} = 2\tilde{S}, \tag{A7}$$

$$\hat{p}_2^S > d \Leftrightarrow S < \frac{r\left(a-c-rd\right)}{8b} = \tilde{S}, \tag{A8}$$

To prove statement *d*) note that $\hat{p}_1 = \overline{p}^S$ when $S = 0$. QED.

Proof of Proposition 5

Statement a) follows from a similar reasoning to that used in the proof of Proposition 4. Statements b), c) and d) follow straightforwardly from the corresponding statements in Lemma 1. QED.

Proof of Proposition 6

Using (38) and (39) in (35), we obtain the equilibrium values for emissions:

$$e_1^*\left(x_1^*, p\right) = \frac{b\left(d_1 - p\right) + t_1 r\left[a + c_2 - 2c_1 - rp\right]}{2bt_1},$$

$$e_2^*\left(x_2^*, p\right) = \frac{2b\left(d_2 - p\right) + rt_2\left(a + 2c_1 - 3c_2 - rp\right)}{4bt_2}.$$

By imposing the non-negativity conditions on the follower's emissions, we obtain the upper bound value for the carbon price, $\overline{p}^{S-2}$:

$$e_2^* \geq 0 \Leftrightarrow p \leq \overline{p}^{S-2} := \frac{2bd_2 + rt_2\left(a - 3c_2 + 2c_1\right)}{2b + r^2 t_2}. \tag{A9}$$

By substitution of the relevant variables in the profit function, we obtain the expression for the leader's profit function in terms of the model parameters:

$$\Pi_1^*(p) = \frac{[a + c_2 - 2c_1 - rp]^2}{8b} + \frac{(p - d_1)^2}{4t_1} + pS_1$$

Differentiating with respect to p, we obtain

$$\frac{\partial \Pi_1^*}{\partial p} = \frac{2b(p - d_1) + 4bt_1S_1 - rt_1[a + c_2 - 2c_1 - rp]}{4bt_1}$$

and, by equating this derivative to zero, we get the minimum value of p such that the leader finds it profitable to push the price up, $\hat{p}_1^{S-2}$:

$$\frac{\partial \Pi_1^*}{\partial p} \geq 0 \Leftrightarrow p \geq \frac{rt_1(a + c_2 - 2c_1) + 2bd_1 - 4bt_1S_1}{r^2t_1 + 2b} := \hat{p}_1^{S-2}. \tag{A10}$$

By direct differentiation of the values of $\overline{p}^{S-2}$ and $\hat{p}_1^{S-2}$, we obtain the results in the proposition:

$$\frac{\partial \overline{p}^{S-2}}{\partial c_1} = \frac{2rt_2}{2b + r^2t_2} > 0; \qquad \frac{\partial \hat{p}_1^{S-2}}{\partial c_1} = \frac{-2rt_1}{2b + rt_1} < 0;$$

$$\frac{\partial \overline{p}^{S-2}}{\partial c_2} = \frac{-3rt_2}{2b + r^2t_2} < 0; \qquad \frac{\partial \hat{p}_1^{S-2}}{\partial c_2} = \frac{rt_1}{2b + rt_1} > 0;$$

$$\frac{\partial \overline{p}^{S-2}}{\partial d_1} = 0; \qquad \frac{\partial \hat{p}_1^{S-2}}{\partial d_1} = \frac{2b}{2b + rt_1} > 0;$$

$$\frac{\partial \overline{p}^{S-2}}{\partial d_2} = \frac{2b}{2b + r^2t_2} > 0; \qquad \frac{\partial \hat{p}_1^{S-2}}{\partial d_2} = 0;$$

$$\frac{\partial \overline{p}^{S-2}}{\partial S_1} = \frac{\partial \overline{p}^{S-2}}{\partial S_2} = 0;$$

$$\frac{\partial \hat{p}_1}{\partial S_1} = \frac{-4bt_1}{2b + rt_1} < 0; \qquad \frac{\partial \hat{p}_1^{S-2}}{\partial S_2} = 0;$$

$$\frac{\partial \hat{p}_1^{S-2}}{\partial t_1} = \frac{2br\left(a + c_2 - 2c_1 - d_1 r\right) - 8b^2 S_1}{\left[r^2 t_1 + 2b\right]} \leq 0 \Leftrightarrow S_1 \leq \frac{r\left(a + c_2 - 2c_1 - d_1 r\right)}{4b};$$

$$\frac{\partial \overline{p}^{S-2}}{\partial t_2} = \frac{2br\left[a - 3c_2 + 2c_1 - rd_2\right]}{\left(2b + r^2 t_2\right)^2} > 0,$$

where, in an interior solution, the numerator of the last expression must be positive for the follower's output to be positive. QED.

Extension of the linear separable case with N firms

In the second stage, the emissions of a firm still depend only on the carbon price and the output of that firm, as in (20), and hence the minimized cost function is still given by (23). Moving on to the output stage, the inverse demand function can be written as

$$P = a - bX = a - bx_i - b\sum_{j \neq i} x_j$$

In the **<u>COURNOT</u>** version, each firm maximizes its own output taking the other firms' as given, which results in the following reaction function for firm *i*:

$$x_i = \frac{a - c - pr - b\sum_{j \neq i} x_j}{2b}$$

Solving the system of equations given by the N reaction functions, we obtain the equilibrium output and the output price:

$$x_i = \frac{a - c - pr}{b\left(N + 1\right)} \qquad i=1,\ldots,N$$

$$P = \frac{a + N\left(c + pr\right)}{N + 1}$$

Emissions turn out to be

$$e_i = \frac{2tr(a-c) - 2tr^2 p + b(N+1)(d-p)}{2bt(N+1)}$$

and then, to ensure that abatement and emissions (and hence output) are nonnegative, we need to impose $d \le p \le \overline{p}^C$, where

$$\overline{p}^C := \frac{2tr(a-c) + (N+1)bd}{2tr^2 + (N+1)b}$$

which is the relevant version of Assumption 1.

Using the equilibrium expressions, the profit of an arbitrary firm, *i*, can be written as

$$\Pi^*_i(p) = \frac{4t(a-c-rp)^2 + b(N+1)^2(p-d)^2 + 4(N+1)^2 bptS}{4(N+1)^2 bt}$$

which is strictly convex in *p* and reaches a minimum at

$$\hat{p}^C := \frac{4tr(a-c) + b(N+1)^2(d-2tS)}{4tr^2 + b(N+1)^2}$$

where we have $d < \hat{p}^C < \overline{p}^C$ and then Proposition 1 holds with the only difference that $\hat{p}^C$ depends now on N.

In the **STACKELBERG** version, assuming that firm 1 is a leader and firms *i*=2,…, *N* are followers, we can write the reaction function of each of the followers as

$$x_i = \frac{a-c-pr-b\left(x_1 + \sum_{j\neq 1,i} x_j\right)}{2b}$$

and the aggregate output of the N-1 followers can be written as

$$x_F = (N-1)x_i = \frac{(N-1)(a-c-pr)}{bN} - \frac{(N-1)x_1}{N}$$

Plugging this expression into the leader's profit function and solving the leader's first order condition, we get the leader's output:

$$x_1^* = \frac{a-c-pr}{2b},$$

which is exactly the same amount that the leader produces in the N=2 case. And using the reaction function, we get the followers' output:

$$x_i^* = \frac{a-c-pr}{2bN} \quad i = 2,\ldots,N .$$

Using these expressions, we can compute equilibrium emissions and, to ensure interior solution, we need to impose $d \le p \le \overline{p}^S$ where

$$\overline{p}^S := \frac{Nbd + rt(a-c)}{Nb + tr^2}$$

which is the relevant version of Assumption 2.

The leader's and the followers' profits are given by

$$\Pi_1^*(p) = \frac{t(a-c-rp)^2 + bN(p-d)^2 + 4bNptS}{4bNt}$$

$$\Pi_i^*(p) = \frac{t(a-c-rp)^2 + bN^2(p-d)^2 + 4bptSN^2}{4btN^2}$$

and it's straightforward to conclude that Proposition 2 still holds with

$$Arg\min_p \Pi_1^*(p) \equiv \hat{p}_1^S = \frac{rt(a-c) + Nbd - 2NbtS}{Nb + tr^2},$$
$$Arg\min_p \Pi_i^*(p) \equiv \hat{p}_i^S = \frac{rt(a-c) + N^2bd - 2N^2btS}{N^2b + tr^2}, \quad \text{i} = 2,\ldots,\text{N}$$

with $d < \hat{p}_i^S < \hat{p}_1^S$.

Comparing the critical values we also conclude $\hat{p}_i^S < \hat{p}^C < \hat{p}_1^S \le \overline{p}^S < \overline{p}^C$ for i=1,…,N, and so Proposition 3 also holds. Proposition 4 can be verified in the same way.